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ORIGINAL ARTICLE

Working memory demands modulate cognitive control in the Stroop paradigm

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Abstract One important task of cognitive control is to regulate behavior by resolving information processing conflicts. In the Stroop task, e.g., incongruent trials lead to conflict-related enhancements of cognitive control and to improved behavioral performance in subsequent trials. Several studies suggested that these cognitive control processes are functionally and anatomically related to working memory (WM) functions. The present study investigated this suggestion and tested whether these control processes are modulated by concurrent WM demands. For this purpose, we performed three experiments in which we combined different WM tasks with the Stroop paradigm and measured their effects on cognitive control. We found that high WM demands led to a suppression of conflict-triggered cognitive control, whereas our findings suggest that this suppression effect is rather due to WM updating than to maintenance demands. We explain our findings by assuming that WM processes interfere with conflict-triggered cognitive control, harming the efficiency of these control processes.

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Introduction

In everyday life, we often focus our attention on behaviorally relevant stimuli while ignoring distracting ones. For example, we are concentrating on writing an article in our office and, at the same time, ignoring the noise outside the window. One basic mechanism behind these phenomena is cognitive control. According to many theoretical approaches, cognitive control is defined as a collection of processes allowing humans to modify their behavior to achieve their action goals (e.g., Baddeley, 1986; Norman & Shallice, 1986).

Recent studies have shown that humans may enhance cognitive control and improve its operation after the occurrence of information processing conflicts. The operation of such enhanced cognitive control is especially reflected by improved conflict resolution in interference tasks in which participants process conflicting response information. In these situations, processing improvements usually occur in an actual trial if participants processed a conflict compared to no conflict in the preceding trial (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Kerns et al., 2004; Stürmer, Leuthold, Soetens, Schröter, & Sommer, 2002; Wühr & Kunde, 2008; but see Mayr, Awh, & Laurey, 2003). Such trial-to-trial modulations were reported by Kerns et al. (2004) for the case of the Stroop task, in which participants name the ink color of a color word and in which reaction times (RT) are increased in incongruent (I) conditions (e.g., the word “RED” in green ink) compared to congruent (C) ones (e.g., “RED” in red ink). Kerns et al. have shown that the interference effect (i.e., the RT difference between I and C trials; Stroop effect) is smaller in trials which are preceded by a conflict trial compared to a non-conflict trial. Similar trial-to-trial modulations were also observed for other interference tasks

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such as the Eriksen-flanker task (Botvinick et al., 2001; Gratton, Coles, & Donchin, 1992) and the Simon task (Stürmer et al., 2002; Stürmer & Leuthold, 2003).

An influential theory of Botvinick et al. (2001) explains the occurrence of trial-to-trial modulations with a specific mechanism of cognitive control. According to that theory, the cognitive system monitors ongoing response processing to identify conflicts. If a conflict is detected, e.g., as a result of stimulus or response processing, the level of cognitive control is enhanced to adjust conflict processing in the subsequent trial. For example, such adjustments may enhance and/or suppress the processing of task-relevant stimulus or response characteristics to enable successful behavior (Botvinick et al., 2001; Egner, Delano, & Hirsch, 2007; Egner & Hirsch, 2005a).

While the theory of Botvinick et al. (2001) allows explaining the occurrence of post-conflict adjustments in the Stroop task and other paradigms and while it is in line with a large body of evidence, an open question refers to the specific factors which determine the efficiency of cognitive control. Previous studies have already shown that such post-conflict adjustments are modulated by the processing demands of supplementary tasks (Fischer, Dreisbach, & Goschke, 2008; Fischer, Plessow, Kunde, & Kiesel, 2010; Stürmer, Seiss, & Leuthold, 2005) or by emotional contexts (van Steenbergen, Band, & Hommel, 2009, 2011). In the present study, we address the question whether an additional working memory (WM) load may affect the efficiency of control-triggered post-conflict adjustments in the Stroop paradigm.

WM functions are of special interest here because converging evidence from different research areas suggests that cognitive control and WM processes rely on related mechanisms. For example, many authors assume that task representations are maintained in WM during ongoing interference task processing (Braver et al., 1997; Kane & Engle, 2003; MacDonald, Cohen, Stenger, & Carter, 2000). Since cognitive control is usually operating on these task representations (e.g., Dreisbach & Haider, 2009), the availability of a sufficient amount of WM resources can be considered as an important precondition for an efficient operation of cognitive control.

In favor of that assumption, several studies have observed that an additional WM load may reduce the efficiency of cognitive control processes (Lavie, Hirst, de Fockert, & Viding, 2004; Schmeichel, 2007; Ward & Mann, 2000). Although these studies investigated other mechanisms than post-conflict adjustments, their findings seem relevant for post-conflict adjustments in interference tasks as well. For example, Lavie et al. reported that the inhibition of task-irrelevant distractors was impaired in a selective attention task by simultaneous WM load. In detail, participants performed a WM task and simultaneously an Eriksen-flanker task in which they reacted on a central target surrounded by distractor stimuli. The WM task required participants to indicate whether a presented probe digit was present or absent in a preceding memory set of either six (high WM load) or one digit (low WM load). Lavie et al. found that the flanker interference effect was larger in the high than in the low WM load condition. According to the authors, the control functions involved in distractor inhibition are closely associated with WM processes, and a larger WM load reduces the resources for distractor inhibition, causing an increased flanker effect. Taken together, these considerations and empirical results are suggestive for the assumption of a close functional relationship between cognitive control and WM processes. In addition, they support the hypothesis that, per analogy, post-conflict adjustments in the Stroop task may be impaired by a simultaneous high WM load.

That hypothesis can also be supported by considering the neuroanatomical basis of WM processes and post-conflict adjustments. For example, Kerns et al. (2004) found a significant negative correlation between the amount of post-conflict adjustments and dorsolateral prefrontal cortex (DLPFC) activity. According to the authors, this correlation suggests that DLPFC activity is closely related to the maintenance of task-relevant information in WM during Stroop task performance (see also Carter et al., 1998; MacDonald et al., 2000). In line with that assumption, several neuroimaging studies suggest that DLPFC activity is generally related to the maintenance and updating of WM contents (Braver et al., 1997; D'Esposito et al., 1998; Garavan, Ross, Li, & Stein, 2000; Schumacher et al., 1996; Smith & Jonides, 1999; Sylvester et al., 2003). Since it is assumed that two processes show strong interference if they share a common neuroanatomical basis (Kinsbourne & Hicks, 1978; Klingberg, 1998), WM processes and cognitive control processes may interfere due to their overlapping neuroanatomy. Hence neuro-scientific considerations provide further support for the expectation that post-conflict adjustments in the Stroop task can be modulated by simultaneous WM demands.

Experimental rationales and hypotheses

The present experiments investigated whether WM demands interfere with cognitive control in the Stroop task. Based on the assumption that cognitive control and WM processes are functionally and anatomically related to each other, we predict that concurrent WM demands in an unrelated task should lead to a reduction of post-conflict adjustments in the Stroop task. We tested this hypothesis by combining the Stroop paradigm with different WM tasks. As WM tasks, we used an arithmetic task in Experiment 1, a version of the n-back paradigm in Experiment 2, and a WM maintenance task in Experiment 3.

It is important to note that some authors questioned the interpretation that sequential trial-to-trial modulations of interference effects result from control-related post-conflict adjustments. For example, Mayr et al. (2003) proposed an alternative account for the explanation of sequential trial-to-trial modulations in the flanker task. This account assumes that episodic memory traces of information of former trials prime stimulus and response features in subsequent trials. Similar considerations have also been proposed by other authors (Davelaar & Stevens, 2009) and for other paradigms (e.g., the Simon task; Hommel, Procter, & Vu, 2004; Wendt, Kluwe, & Peters, 2006). However, we note that a priming-based explanation is not sufficient as a sole explanation for the observed trial-by-trial modulations in the Stroop task as they can be observed even after removing all feature repetition trials (Puccioni & Vallesi, in press). To address the possibility of a priming-based explanation of our results, we controlled for different types of feature repetition effects when analyzing post-conflict adjustments.

Experiment 1

Experiment 1 tested whether concurrent WM demands interfere with post-conflict adjustments in the Stroop task. Participants performed a Stroop task together with a WM task, which was presented either in a high load or a low load condition. In the high load condition of the WM task, participants had to maintain two numbers in WM and to count up or down in steps of two from one of these numbers. Consequently, this task required the updating and monitoring of WM contents. In the low load condition, we presented only the arithmetic stimuli in addition to the Stroop task. Participants were instructed to attend to these stimuli without performing arithmetic operations. Consequently, participants had to maintain a second task representation additionally to the representation of the Stroop task in WM both in the high load and the low load conditions, but the task was much more demanding in the high load (perform arithmetic operations) than in the low load condition (attend to presented stimuli). In a third single-task condition, participants performed the Stroop task in isolation with no additional second-task instructions and stimuli.

Methods

Participants

Twenty-eight right-handed participants ($M_{\text{age}} = 24.21$ years; 20 female) were recruited by advertisement at the Department of Psychology at the LMU Munich and were paid 8€/hour for their participation. All subjects had normal or corrected-normal vision and were not informed about the aims of the experiment.

Stimuli and apparatus

The experiment took place in a dimly-lit soundproof experimental cabin. The participants sat 50 cm in front of a 17 in. monitor on which stimuli were presented. All stimuli were presented with Experimental Run Time System (ERTS, Behringer, 1993) on a standard PC.

As illustrated in Fig. 1, participants performed three different tasks: the Stroop task, the high WM load task and the low WM load task. In the *Stroop task*, participants were presented one of three different color words (“BLAU”, “ROT”, and “GRÜN”; German for *blue*, *red*, and *green*, respectively) written in capital letters colored either in blue, red, or green ink on a black screen. Participants were instructed to respond to the color of the stimuli as fast and as accurately as possible by pressing the “B”-key (for blue) with the index finger, the “N”-key (for red) with the middle finger or the “M”-key (for green) with the ring finger of the right hand on a QWERTZ-keyboard.

In the *high WM load task*, three white “x” were presented as fixation cross row on a black screen, whereas either the left or the right “x” could change into a plus (+) or a minus (−) sign. In each block, participants started with the number “50” both for the “x” at the left and the right position and performed the arithmetic operations shown at

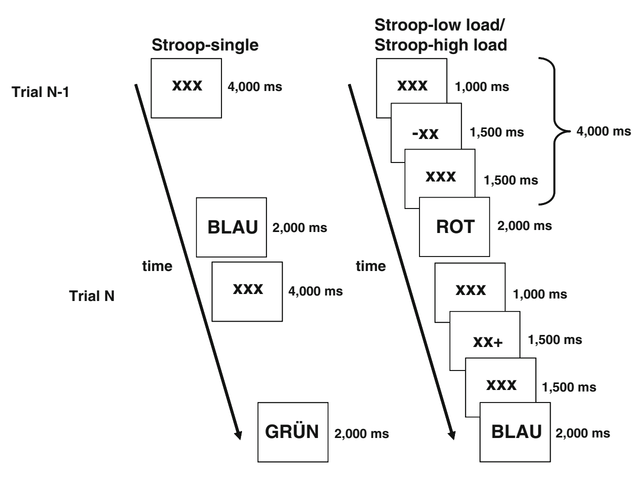

Fig. 1 Example trial sequences for the different task conditions in Experiment 1. The procedure was identical for the Stroop-low load and the Stroop-high load condition. In the Stroop-high load condition, participants performed the Stroop and the arithmetic task, while in the Stroop-low load condition they were instructed to perform the Stroop task and to attend the arithmetic stimuli. The Stroop task stimuli were presented in blue, red or green color, and all other stimuli were presented in white

the left "x" with the first number in mind and the operations presented at the right "x" with the second number in mind. To increase task difficulty, they were instructed to add "2" if a plus sign was presented and to subtract "2" if a minus was presented. For example, if a plus sign was presented at the right position (the left and the central "x" stayed unchanged in this case), then participants had to add "2" to the second number in WM while the first number remained unchanged compared to the preceding trial (note that only one arithmetic stimulus was presented in each trial). Thus, participants always had to maintain two numbers in WM and to conduct arithmetic operations on them. After each block including the high WM load task, the two final results of the continuous arithmetic calculations had to be written on a separate sheet of paper. In the *low WM load task*, the same stimuli were presented as for the arithmetic high WM load task, i.e., the three "x" as fixation cross row, whereas in every trial either the left or right "x" changed into a plus or minus sign. Participants were instructed to attend to these stimuli without performing arithmetic operations with them.

All stimuli were presented in 18-point size of Helvetia Font.

Design and procedure

Participants performed the Stroop task in three different WM load conditions: Stroop-single, Stroop-high load, and Stroop-low load. While the Stroop task was performed in isolation in the Stroop-single condition, it was combined with the high WM load and the low WM load task in the Stroop-high load and Stroop-low load conditions, respectively. In addition to the Stroop task conditions, participants performed the high WM load task in isolation in the high load-single condition.

In the Stroop task conditions (i.e., Stroop-single, Stroop-high load, and Stroop-low load), each block consisted of 12 (27%) incongruent and 33 (73%) congruent trials (see Kerns et al., 2004). Note that the ratio of C and I trials is supposed to trigger proactive control processes which may have to be distinguished from the post-conflict adjustments we were interested in (Funes, Lupiáñez, & Humphreys, 2010). But since these proactive control processes are assumed to have equal effects on conflict processing after previously congruent and incongruent trials (i.e., the level of proactive control is constant across all trials of a block), they should not confound with our analysis of post-conflict adjustments.

Trial order was randomized with the following two constraints: First, the number of CI (previous trial C, current trial I) and II trial sequences was equal per block (6 trials each). Second, the same number of congruent trials with a blue, red, or green word was followed by an incongruent one (thus 2 trials each, as we administered 6 CI trial sequences). In the high WM load conditions, the number of arithmetic signs (+ vs. −) and their specific location (left vs. right) differed across blocks to prevent predictability of the final results.

In the *Stroop-single* condition, a trial started with a foreperiod of 4,000 ms in which three white "x" were shown at the center of the screen, then a color word was presented for 2,000 ms or until a response was executed. Participants had to respond within the stimulus presentation time for the color word, then the next trial started immediately after the response. Also in the *high load-single* condition, the foreperiod including the presentation of three white "x" took 4,000 ms, then an arithmetic sign was displayed for 2,000 ms on the left or right position. In the *Stroop-high load* and *Stroop-low load* conditions, the basic procedure was as follows: After a foreperiod of 1,000 ms in which the fixation cross row (i.e., the three "x") was displayed, one of the two outer crosses changed into a plus or a minus sign for 1,500 ms. After an inter-stimulus interval (ISI) of further 1,500 ms, the color word of the Stroop task was presented for an interval of 2,000 ms or until a response was executed. In the Stroop-high load condition, we instructed participants to perform the Stroop and the high WM load task simultaneously with equal priority, while in the Stroop-low load condition they were instructed to perform the Stroop task and to attend to the arithmetic stimuli but to perform no arithmetic operations.

Half of the participants started the experiment with eight blocks of the single conditions, i.e., Stroop-single and high load-single, in alternating order. The first type of block was balanced across participants. Following, eight blocks of dual-task conditions, i.e., Stroop-high load and Stroop-low load, were presented in alternating order and with balanced starting block type. For the remaining half of participants, the order of single-task and dual-task conditions was changed.

Statistical analysis

In the Stroop task conditions, RTs and error rates were analyzed. We removed all trials in which the target or distractor feature was repeated as target or distractor, respectively (39% of all Stroop trials; Kerns et al., 2004) to control for the effects of such feature repetitions on the trial-by-trial modulations of the Stroop effect (Mayr et al., 2003). In addition, we performed further analyses controlling for possible negative priming effects (see below). For the RT analysis of the Stroop task, we furthermore removed all trials including or following an error. As a result of these exclusions, a mean of 412 trials per participant was included in the analysis. Post-conflict adjustments were defined as the RT difference between the Stroop effect after previously congruent trials and the

Stroop effect after previously incongruent trials (CI-CC)-(II-IC).

To analyze performance in the high WM load task, we computed the difference between the true and the calculated final results in every block and averaged the difference values separately for all high load-single blocks and all Stroop-high load blocks.

For tests of significance, ANOVAs and paired-sample *t* tests as planned comparisons were used with a significance threshold of 5%. Huynh–Feldt corrections (Huynh & Feldt, 1976) were used to adjust the *p* values of the ANOVAs. As effect sizes, partial eta square (η_p^2) was calculated for the ANOVAs.

Results

Stroop task

Reaction times We analyzed RTs (see Fig. 2) in the Stroop task by conducting a 3 × 2 × 2 repeated-measures ANOVA with the factors WM load (Stroop-single vs. Stroop-low load vs. Stroop-high load), Previous trial congruency (congruent vs. incongruent) and Current trial congruency (congruent vs. incongruent). The analysis revealed a significant main effect of WM load, $F(2, 54) = 15.38$, $p < .001$, $\eta_p^2 = 0.363$: Mean RTs were larger in the Stroop-high load ($M = 806$ ms) than in the Stroop-single ($M = 700$; $p < .001$) and the Stroop-low load conditions ($M = 712$; $p < .001$), while no significant difference was found between the last two conditions ($p > .3$). Participants responded faster in currently congruent ($M = 686$) than in incongruent trials ($M = 868$), $F(1, 27) = 94.02$, $p < .001$, $\eta_p^2 = 0.777$. Furthermore, the significant interaction between previous trial congruency and current trial congruency, $F(1, 27) = 10.76$, $p < .01$, $\eta_p^2 = 0.285$, pointed to the occurrence of post-conflict adjustments. Most importantly, the three-way interaction between WM load, previous trial congruency, and current trial congruency was significant, $F(2, 54) = 5.26$, $p < .05$, $\eta_p^2 = 0.163$. This suggests that the amount of the post-conflict adjustments depended on the task condition.

Next, we calculated planned comparisons to determine in which way post-conflict adjustments were modulated by WM load. We found significant post-conflict adjustments only in the Stroop-single, (CI-CC)-(II-IC) = 106 ms, $t(27) = 3.54$, $p < .001$, and in the Stroop-low load conditions, (CI-CC)-(II-IC) = 56 ms, $t(27) = 2.53$, $p < .05$, but not in the Stroop-high load condition, (CI-CC)-(II-IC) = −15 ms, $t(27) < 1$, $p > .5$. In addition, we tested whether the amount of the post-conflict adjustments differed between the task conditions. We found that post-conflict adjustments were significantly reduced in the Stroop-high load relative to the Stroop-single, $t(27) = 2.76$, $p < .01$, and to the Stroop-low load conditions, $t(27) = 2.08$, $p < .05$. No significant difference was found between the Stroop-single and the Stroop-low load conditions, $t(27) = 1.19$, $p > .1$.

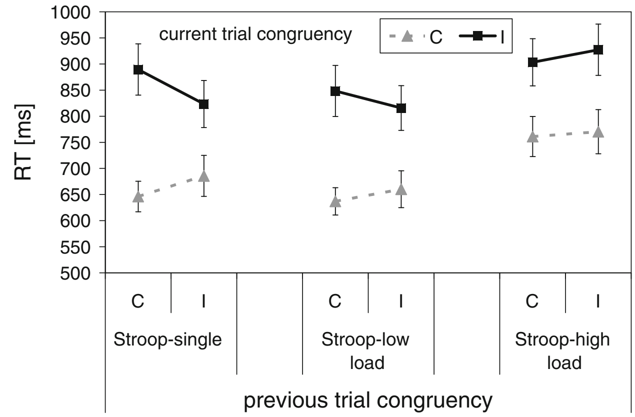

Fig. 2 Mean reaction times (RTs) in the Stroop task conditions in Experiment 1. *Error bars* indicate the standard error of mean (*C* congruent, *I* incongruent)

Note that we removed all trials from our analysis that included a repetition either of the color or the word feature, called within-dimension repetitions to exclude an impact of such feature repetitions on post-conflict adjustments (Hommel et al., 2004; Mayr et al., 2003). In addition, we controlled for possible influences of negative priming effects on our findings by adopting a different approach than that for controlling for the within-dimension feature repetition effects. In particular, negative priming may occur when the distractor feature of the previous trial becomes target feature in the current trial, or vice versa (across-dimension repetitions). It is important to note that, to control for influences of such across-dimension repetitions, we could not simply exclude the corresponding trials from the analysis (in addition to the exclusion of the within-dimension repetition trials) because this would have led to a complete removal of all II trials in the Stroop paradigm. Therefore, to test for possible negative priming influences, we calculated post-conflict adjustments in the three Stroop task conditions twice, i.e., once after removing all trials with within-dimension repetitions (the usual procedure in experiments with the Stroop paradigm, Egner, 2007; Kerns et al., 2004) and once after removing all trials with across-dimension repetitions. Next, we entered the resulting values into an ANOVA with the amount of post-conflict adjustments as dependent variable and with excluded trial type (within-dimension repetitions vs. across-dimension repetitions) and WM load (Stroop-single vs. Stroop-low load vs. Stroop-high load) as within-subject factors (for a similar procedure, see Egner & Hirsch, 2005a). Most importantly, the results of this ANOVA showed similar effects of WM load on the amount of post-conflict adjustments independently of which way the trial exclusion procedure was adopted. Thus, the current effects are not confounded by possible negative priming effects and effects of across-dimension feature repetitions. In detail, a significant main effect of WM load indicated that the amount of the post-conflict adjustments depended on the level of WM load, $F(2,\ 54) = 3.46$, $p < .05$, $\eta_p^2 = 0.114$, while the lacking effects of excluded trial type and the interaction between excluded trial type and WM load, both Fs < 1, suggested that the modulation of post-conflict adjustments is independent of which trials were excluded from the analysis. This is consistent with the assumption that the current WM load effects on the post-conflict adjustments are not confounded by possible negative priming effects and effects of across-dimension repetitions.

Error rates We analyzed error rates with a repeated-measures ANOVA including the factors WM load, Previous trial congruency, and Current trial congruency. Only the main effects of current trial congruency, $F(1, 27) = 77.55$, $p < .001$, $\eta_p^2 = 0.742$, and previous trial congruency, $F(1, 27) = 6.00$, $p < .05$, $\eta_p^2 = 0.182$, passed the statistical threshold. Subjects committed more errors in incongruent ($M = 7.5\%$) than in congruent trials ($M = 2.7\%$) and following congruent trials ($M = 5.8\%$) compared to following incongruent trials ($M = 4.4\%$). No other main effect or interaction was significant (see Table 1).

WM task

Performance rates We compared the performance rates in the WM task under dual-task and single-task conditions with a paired-sample t test. The significant difference between the error rates in the high load-single ($M = 3.7$) and the Stroop-high load condition ($M = 6.6$), $t(27) = 3.67$, $p < .01$, shows that performance in the WM task deteriorated in the dual-task condition.

Discussion

Experiment 1 investigated whether post-conflict adjustments can be modulated by WM demands. While no post-conflict adjustments occurred in the Stroop-high load condition, we found significant post-conflict adjustments both in the Stroop-single and the Stroop-low load conditions. Most importantly, post-conflict adjustments were significantly reduced in the Stroop-high load relative to the Stroop-low load condition. This is consistent with the assumption that post-conflict adjustments in the Stroop task can be modulated by additional WM demands. The observed modulation of post-conflict adjustments was independent of which kinds of feature repetition trials were excluded from the analysis, suggesting that this effect cannot be explained by a feature priming account.

Against the proposed explanation of the modulated post-conflict adjustments, one might argue that the secondary task in the Stroop-low load condition might not have exposed any additional WM demands and participants might have processed that condition as a Stroop-single task and not in a dual-task mode. Such an argument may, in theory, be raised because for this type of secondary task, there was no control for participants' performance and attention to the presented stimuli. Therefore, we conducted Experiment 2 in which we administered a different WM task than that in Experiment 1, which allowed us to control for the impact of different levels of a concurrent WM load on the performance in post-conflict adjustments.

Table 1 Error rates (in percent) in the Stroop task conditions of Experiment 1

Previous trial congruency:	C		I	
Current trial congruency:	C	I	C	I
Stroop-single	2.7 (.4)	12.7 (2.9)	2.5 (1.3)	6.2 (1.6)
Stroop-low load	2.7 (.7)	9.1 (3.)	1.4 (1.0)	6.5 (1.6)
Stroop-high load	4.9 (2.3)	10.9 (3.8)	7.2 (2.1)	9.7 (2.9)

Standard errors of mean are in brackets

C congruent, *I* incongruent

Experiment 2

In Experiment 2, we combined the Stroop task with a letter-variant of the n-back paradigm, which allowed manipulating the WM load of a secondary task in several steps (Braver et al., 1997). In the n-back task, a stream of letters was sequentially presented to the participants who decided whether a currently presented letter was identical to a previously (n-back) presented one. In the case that they were identical, participants responded with a finger key-press reaction, while no keypress reaction was required in the remaining cases.

We manipulated WM load in three steps: In the 2-back condition, participants had to report whether a currently presented letter was identical to the letter two trials before, while in the 1-back condition they had to respond if a letter was repeated in two subsequent trials. In addition, we administered a 0-back condition in which participants had to respond to a pre-specified letter. Thus, contrary to Experiment 1, the current control condition (0-back) exposed an apparent WM load in a controlled way because at least one item had to be maintained in WM.

The current n-back task required the maintenance and updating of WM contents and, in addition, the monitoring of overt motor response execution (Morris & Jones, 1990). Since overt motor response monitoring processes may affect Stroop task performance, we restricted our analyses of the Stroop task to those trials in which no overt response to an n-back target occurred. This is necessary because Stürmer et al. (2005) have shown that the need for overt motor response monitoring in a secondary task condition may suppress the occurrence of post-conflict adjustments in an interference task. In the study of Stürmer et al., participants performed a Simon task simultaneously with a two-choice and a simple response time task, and in both cases post-conflict adjustments were decreased relative to the Simon task alone. Consequently, by restricting the analysis to trials without overt motor responses in the n-back task, we can investigate the influence of a concurrent WM load on the Stroop task performance in Experiment 2.

Methods

Participants

Seventeen right-handed participants ($M_{\text{age}} = 26.24$ years; 13 females) were recruited for the experiment at the Department of Psychology at the LMU Munich and were paid 8€/hour. All had normal or corrected-to-normal vision and were not informed about the hypotheses of the experiment.

Stimuli and apparatus

The apparatus was identical to that in Experiment 1.

Participants performed the Stroop and the n-back task. The Stroop task was performed in the same way as in Experiment 1 with the only difference that a single "+" was used as fixation cross. For the n-back task, we used a letter-version of the n-back procedure of Braver et al. (1997) in which white letters were successively presented on a black screen. In the 1-back and the 2-back conditions, participants were asked to indicate whether the currently presented letter (= the target stimulus) was identical to the letter presented one or two trials before (= the cue stimulus), respectively, by pressing the left shift key on the keyboard with their left index finger. Therefore, both conditions required the permanent updating and maintenance of information in WM. We used phonologically similar letters in German (B D G P T W) to increase task difficulty.

In the 0-back condition, participants had to press the shift key with the left index finger only if a specific letter was presented on the screen. The instruction before each 0-back block indicated which letter represented the target stimulus in the subsequent block. The 0-back condition required mainly selective attention and response monitoring and, relative to the 1-back and 2-back conditions, a smaller maintenance load and no updating of information in WM.

Design and procedure

Participants performed three different task conditions in which they performed the Stroop task and simultaneously an n-back task (Stroop-0-back, Stroop-1-back, and Stroop-2-back). For the Stroop task, the trial order within one block was randomized with the same constraints as in Experiment 1, however one block contained 90 trials (66 congruent, 24 incongruent). For the n-back conditions, the order of the letters was randomized whereas each of the 6 letters was presented 15 times. Every block contained a total of 18 target stimuli.

The basic procedure was identical for all task conditions. After a foreperiod of 800 ms, a letter for the n-back task was presented (1,000 ms) and then, after an ISI of 1,200 ms, the color word for the Stroop task followed for 2,000 ms. Participants had to respond to the Stroop stimulus during the stimulus presentation time, afterwards the next trial started. We presented three blocks of each of the three experimental conditions in randomized order during the experiment. We instructed participants to respond as fast and as accurately as possible in the Stroop task, while they should mainly try to avoid errors in the n-back task. Since we wanted all participants to use the same strategy in the n-back task, participants were, in addition, instructed to solve the 1-back and 2-back task by internally rehearsing the last one or two presented letters, respectively.

Statistical analysis

For the Stroop task analysis, we removed all trials which contained either a repetition of the color or the word from the data set (38% of all trials). For the RT analysis, we also removed all error and post-error trials and, in addition, all trials in which participants had responded to an n-back stimulus, such that finally a total of 290 trials were included in the analysis.

To analyze performance in the n-back task, we calculated performance rates for every participant and n-back condition. The performance rate was defined as the number of correct answers divided by the number of all target stimuli.

Statistical tests were computed in the same way as in Experiment 1.

Results

Stroop task

Reaction times We computed a $3 \times 2 \times 2$ repeated-measures ANOVA including the factors WM load (Stroop-0-back vs. Stroop-1-back vs. Stroop-2-back), Previous trial congruency (congruent vs. incongruent), and Current trial congruency (congruent vs. incongruent). The results are illustrated in Fig. 3. The significant main effect of WM load indicated different RTs across the Stroop task conditions, $F(2, 32) = 9.86$, $p < .001$, $\eta_p^2 = 0.381$. In more detail, RTs were slower in the Stroop-2-back than in the Stroop-0-back and the Stroop-1-back conditions ($ps < .001$). In addition, RTs were slower in currently incongruent (750 ms) than in congruent trials (590 ms), $F(2, 32) = 67.37$, $p < .001$, $\eta_p^2 = 0.808$, pointing to the occurrence of a Stroop effect of 160 ms. This effect of current trial congruency was modulated by the factor WM load, $F(2, 32) = 4.64$, $p < .05$, $\eta_p^2 = 0.255$, suggesting that the amount of the Stroop effect differed between the WM load conditions. Additional post hoc analyses of the Stroop effect after previously congruent trials showed that the Stroop effect was significantly reduced in the Stroop-2-back (133 ms) compared to the Stroop-0-back (180 ms) and Stroop-1-back (183 ms) conditions, both $ps < .05$.

The Current trial congruency × Previous trial congruency interaction was not significant, $F(2, 32) < 1$, $p > .5$. Importantly, however, the significant WM load x Current trial congruency x Previous trial congruency interaction, $F(2, 32) = 3.97$, $p < .05$, $\eta_p^2 = 0.199$, suggested that the amount of post-conflict adjustments depended on the level of WM load. Planned comparisons revealed that significant post-conflict adjustments occurred only in the Stroop-0-back, (CI-CC)-(II-IC) = 48 ms, $t(16) = 2.16$, $p < .05$, but not in the Stroop-1-back, (CI-CC)-(II-IC) = 2 ms, $t(16) < 1$, $p > .9$, and the Stroop-2-back conditions, (CI-CC)-(II-IC) = = −17 ms, $t(16) < 1$, $p > .5$. Importantly, the amount of post-conflict adjustment was significantly larger in the Stroop-0-back than in the Stroop-1-back, $t(16) = 2.04$, $p < .05$, one-tailed, and in the Stroop-2-back conditions, $t(16) = 2.75$, $p < .01$, one-tailed.

As for Experiment 1, we investigated whether the observed modulation of post-conflict adjustments remained stable when controlling for possible negative priming effects. For that purpose, we applied the same procedure as in Experiment 1 for analyzing whether the effect of the WM load on the post-conflict adjustments would change if we exclude trials with within-dimension repetitions or trials with across-dimension repetitions from the data set (see also Results section of Experiment 1). An ANOVA with the amount of post-conflict adjustments as dependent variable and with the factors Excluded trial type (within-dimension repetitions vs. across-dimension repetitions) and WM load (Stroop-0-back vs. Stroop-1-back vs. Stroop-2-back) revealed a significant main effect of WM load, $F(2, 32) = 6.65$, $p < .01$, $\eta_p^2 = 0.294$. Importantly, neither the main effect of excluded trial type nor the Excluded trial type x WM load interaction was significant, $ps > .14$, indicating that the observed modulation of the post-conflict adjustments was independent of which trials were excluded

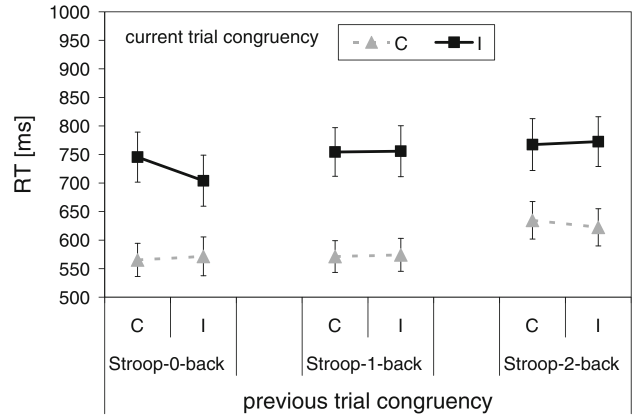

Fig. 3 Mean reaction times (RTs) in the Stroop task of Experiment 2. The *error bars indicate* the standard error of mean (*C* congruent, *I* incongruent)

from the analysis. In other words, the current WM load effects on the post-conflict adjustments are not confounded by possible negative priming effects and effects of across-dimension repetitions.

Error rates We analyzed error rates by a repeated-measures ANOVA including the factors WM load, Previous trial congruency, and Current trial congruency. Only the main effect of current trial congruency was significant, $F(1, 16) = 13.82$, $p < .01$, $\eta_p^2 = 0.463$; more errors were committed in incongruent (9.2%) than in congruent trials (3.5%). No further effect or interaction passed the statistical threshold (see Table 2).

WM task

Performance rates We analyzed performance rates in the n-back task by conducting a repeated-measures ANOVA including the factor WM load (Stroop-0-back vs. Stroop-1-back vs. Stroop-2-back). The main effect of WM load was significant, $F(2, 32) = 12.32$, $p < .001$, $\eta_p^2 = 0.445$. Participants showed the best performance rate in the 0-back task (98%), followed by the 1-back (88%) and, finally the 2-back task (72%), all $ps < .05$.

Discussion

The data of Experiment 2 revealed significant post-conflict adjustments only in the Stroop-0-back, but not in the Stroop-1-back and the Stroop-2-back conditions. Importantly, while post-conflict adjustments did not differ between the Stroop-1-back and the Stroop-2-back conditions, they were significantly reduced in these conditions compared to Stroop-0-back blocks. Hence, the data of Experiment 2 show that high WM demands (which were

Table 2 Error rates (in percent) in the Stroop task conditions of Experiment 2

Previous trial congruency:	C		I	
Current trial congruency:	C	I	C	I
Stroop-0-back	2.2 (.4)	7.5 (1.4)	1.9 (.3)	6.7 (1.3)
Stroop-1-back	3.3 (.6)	7.6 (.6)	1.8 (.3)	6.8 (1.3)
Stroop-2-back	4.2 (.8)	9.9 (1.9)	2.6 (.5)	6.6 (1.3)

Standard errors of mean are in brackets

C congruent, *I* incongruent

present both in the Stroop-1-back and the Stroop-2-back conditions) lead to a suppression of conflict-triggered cognitive control, being consistent with the main hypothesis of the current work.

In addition, the current experiment allows rejecting an important counter argument which may be related to the current dual-task methodology: According to that argument, the reduced post-conflict adjustments in the 1-back and 2-back conditions might be explained by the requirement to permanently switch between the Stroop and the corresponding n-back task, instead of by the concurrent WM demands (see also discussion of Experiment 1). Importantly, however, also the Stroop-0-back condition clearly represents a dual-task situation in which participants have to switch between the Stroop and the 0-back task in every trial. Since the post-conflict adjustments in the Stroop-1-back and Stroop-2-back conditions were significantly reduced relative to the Stroop-0-back condition, task switching demands cannot account for the observed modulation of post-conflict adjustments. Instead, this effect must specifically be explained by the higher WM demands of the 1-back and 2-back compared to the 0-back task.

The results of Experiment 2 furthermore allow discussing the question of which specific WM processes are responsible for the suppression of post-conflict adjustments. A cognitive process which was required by the 1-back and 2-back tasks, but not by the 0-back task, is the updating of WM contents (Braver et al., 1997). This process requires the repeated substitution of the current WM content by another relevant WM content, which differs from the pure maintenance of WM content over a longer period of time. Consequently, the requirement for permanent WM updating seems to have impaired the enhancement of cognitive control after the detection of a conflict, resulting in suppressed post-conflict adjustments.

However, an open question concerns whether increasing demands for pure maintenance of items in WM would affect the occurrence of post-conflict adjustments just as the updating requirement. This question is of interest because the 0-back condition in Experiment 2 required maintaining only one item in WM and this represents a fairly low maintenance demand. To test whether larger demands on the pure maintenance of items in WM would or would not affect the amount of post-conflict adjustments we conducted Experiment 3. In this experiment, we applied a WM task as secondary task, which exposed different demands on WM maintenance and which spared the updating component.

Experiment 3

In Experiment 3, we combined the Stroop task with a WM task in which participants had to maintain either one or six numbers in the WM. The numbers were presented at the start of each Stroop task block. After each block, we asked participants which numbers had been presented at the start of the block. Consequently, this task required the maintenance but not the updating of WM contents during Stroop task performance. This paradigm allowed us to test whether high demands on WM maintenance lead to a reduction of post-conflict adjustments.

Methods

Participants

Fifteen right-handed participants ($M_{age} = 27.13$ years; 10 females) were recruited at the Department of Psychology at the LMU Munich and were paid 8€. All had normal or corrected-to-normal vision and were not informed about the hypotheses of the experiment.

Stimuli and apparatus

The apparatus was identical to the one in Experiment 1.

Participants performed the Stroop and the n-back task. The Stroop task was performed in the same way as in Experiment 2. For the WM task, participants had to memorize either one number (low load) or six numbers (high load) between zero and nine at the start of each block. At the end of a block, i.e., after the Stroop task trials, participants had to enter these numbers on the keyboard.

Design and procedure

Participants performed the Stroop task and simultaneously either the low load (Stroop-low load) or high load WM task (Stroop-high load). Every block contained 12 Stroop task trials (9 congruent, 3 incongruent) which were presented in randomized order and which had a similar ratio of congruent (75%) to incongruent (25%) trials as the task blocks in the Experiments 1 and 2. The procedure was identical for all conditions. At the start of a block, the numbers for the WM task were presented for 5,000 ms, followed by the Stroop task trials. After an ISI of 1,500 ms at the start of these trials, a color word was presented for 2,000 ms or until participants executed a response, then the next trial started. At the end of the block, we asked participants which numbers had been shown at the start of the block.

Participants performed 30 blocks of both the Stroop-low load and the Stroop-high load conditions in randomized order, resulting in a total of 270 congruent and 90 incongruent trials for each condition.

Statistical analysis

We analyzed the Stroop task trials in the same way as in the previous experiments. We removed 27% of all trials due to stimulus repetitions. In addition, we removed all blocks in which the WM task was not solved correctly, as well as error and post-error trials, such that on mean, a total of 216 trials were included in the analysis.

In the WM task, we considered a response as correct only if all numbers presented at the start of a block were correctly replicated. Performances rates were calculated as the percentage of correct responses of all responses in the low load or high load condition.

We computed statistical tests in the same way as in the previous experiments.

Results

Stroop task

Reaction times We computed a 2 × 2 × 2 repeated-measures ANOVA including the factors WM load (Stroop-low load vs. Stroop-high load), Previous trial congruency (congruent vs. incongruent) and Current trial congruency (congruent vs. incongruent). The findings are depicted in Fig. 4. RTs were slower in incongruent (642 ms) than in congruent trials (534 ms), $F(1,\ 14) = 51.37$, $p < .001$, $\eta_p^2 = 0.786$, and after previously incongruent (580 ms) than after congruent trials (565 ms), $F(1,\ 14) = 10.16$, $p < .01$, $\eta_p^2 = 0.420$. The significant Current trial congruency × Previous trial congruency interaction points to the occurrence of post-conflict adjustments, $F(1,\ 14) = 8.41$, $p < .05$, $\eta_p^2 = 0.375$: We found significant post-conflict adjustments both in the Stroop-low load, (CI-CC)-(II-IC) = 39 ms, $t(14) = 1.85$, $p < .05$, one-tailed, and the Stroop-high load conditions, (CI-CC)-(II-IC) = 50 ms, $t(14) = 2.48$, $p < .05$, one-tailed. Importantly, the WM load × Current trial congruency x Previous trial congruency interaction was not significant, $F(1,\ 14) < 1$, $p > .7$, $\eta_p^2 = 0.011$, which suggests that the number of items maintained in WM has no impact on the occurrence of post-conflict adjustments in the current paradigm.

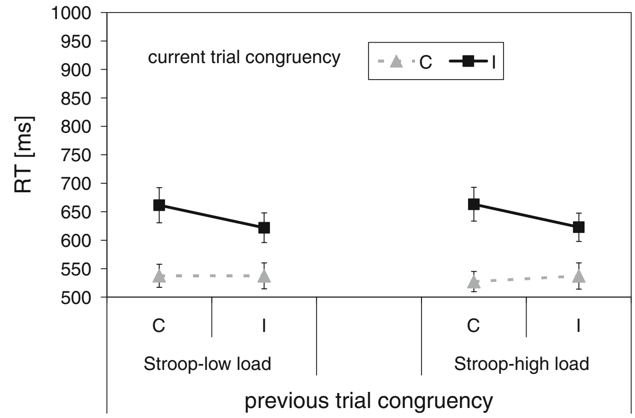

Fig. 4 Mean reaction times (RTs) in the Stroop task of Experiment 3. The *error bars* indicate the standard error of mean (*C* congruent, *I* incongruent)

As in the pervious experiments, we controlled for possible negative priming effects by calculating an ANOVA including the amount of post-conflict adjustments as dependent variable and the factors Excluded trial type (within-dimension repetitions vs. across-dimension repetitions) and WM load (Stroop-low load vs. Stroop-high load). No effect passed the statistical threshold, all Fs < 1.

Error rates A repeated-measures ANOVA including the same factors as the RT analysis revealed that participants committed more errors in currently incongruent (8.2%) than in congruent trials (3.1%), $F(1,\ 14) = 21.86$, $p < .001$, $\eta_p^2 = 0.610$, as well as after previously congruent (5.2%) than after incongruent trials (4.0%), $F(1,\ 14) = 7.45$, $p < .05$, $\eta_p^2 = 0.347$. No further effect was significant (see Table 3).

WM task

Performance rates A paired-sample t test showed that performance rate was higher in the low load (98%) than in the high load condition (94%), $t(14) = 2.83$, $p < .05$.

Discussion

The results of Experiment 3 show that the number of items maintained in WM does not affect conflict-triggered control. In detail, the amount of post-conflict adjustments did not depend on whether the task was to maintain one (low load) or six items (high load). Note that the higher error rate in the high load compared to the low load task shows that the high load task was more difficult and thus required more WM efforts than the low load task, even if participants had used a chunking strategy, which would have reduced the number of stored chunks below six items (see Miller, 1956). Moreover, performance rate in the high load

Table 3 Error rates (in percent) in the Stroop task conditions of Experiment 3

Previous trial congruency:	C		I	
Current trial congruency:	C	I	C	I
Stroop-low load	4.1 (.7)	10.4 (1.6)	2.7 (1.3)	6.1 (1.7)
Stroop-high load	3.3 (.6)	9.1 (2.2)	.0 (.0)	7.3 (1.3)

Standard errors of mean are in brackets

C congruent, *I* incongruent

condition of Experiment 3 was similar to the performance rate in the 1-back condition of Experiment 2 (in which no post-conflict adjustments occurred), suggesting that these two WM tasks were of comparable difficulty. Consequently, increased demands on WM maintenance processes had no effect on the operation of post-conflict adjustments in Experiment 3.

General Discussion

The purpose of the present study was to investigate whether WM demands modulate post-conflict adjustments in the Stroop task. In Experiments 1 and 2, we found no post-conflict adjustments in the Stroop task when participants simultaneously performed a demanding WM task (an arithmetic task, or a 1-back and a 2-back task, respectively), while significant post-conflict adjustments occurred when participants performed a secondary task with less WM demands (Stroop-low load or Stroop-0-back condition) or the Stroop task alone (Stroop-single condition). The finding of significantly reduced post-conflict adjustments in the Stroop-1-back compared to the Stroop-0-back condition suggests that updating and not maintenance of WM contents led to a suppression of conflict-triggered control, since the demands on WM maintenance should not have differed between the 0-back and the 1-back condition.

This conclusion is supported by the results of Experiment 3: Significant post-conflict adjustments occurred even when participants simultaneously maintained six numbers in WM, hence a number of items which is clearly larger than the number of WM items in the 1-back task (one item). Taken together, these results suggest that simultaneous demands on WM updating interfere with conflict-triggered cognitive control in the Stroop task, while the simple maintenance of up to six items in WM had no effect on these control processes in Experiment 3. Note that a conclusion that WM maintenance does not impair post-conflict adjustments at all must be considered with caution, since we cannot be sure about the impact of a load higher than six items on post-conflict adjustments (even though the number of six items is already close to the maximum WM capacity, Miller, 1956).

The observed interference between WM demands and cognitive control fits well with current assumptions about the processes involved in the two mechanisms and their neural implementation: First, current theoretical approaches suggest that cognitive control and WM processes are functionally interdependent. Cognitive control processes are involved in the selection of information that enters WM (Baddeley, 1986; Hasher & Zacks, 1988) and, moreover, the operation of cognitive control requires the maintenance and updating of task representations in WM and hence the availability of WM resources (Dreisbach & Haider, 2009; MacDonald et al., 2000). Second, these functional considerations were supported by neuroanatomical findings suggesting that overlapping brain regions such as the DLPFC and the anterior cingulate cortex are involved both in WM processes and post-conflict adjustments. The results of the present study clearly fit with the predictions based on these functional and anatomical considerations and moreover also with the findings of previous studies which reported an impairment of other cognitive control processes by WM demands (Lavie et al., 2004; Schmeichel, 2007; Ward & Mann, 2000).

An important issue which needs to be discussed is which reasons can be accounted for the observed reductions of post-conflict adjustments. Several possible explanations have to be discussed: First, according to a view that was recently substantiated by Schmeichel (2007), it is possible that WM and cognitive control processes both require the same capacity-limited processing resources. If this is correct, then specific executive control processes required in the Stroop task and memory updating processes would share a common resource, i.e., common processing mechanisms. According to that view, the suppression of post-conflict adjustments occurs because the WM demands deplete all available processing resources so that no further cognitive control could be executed after the occurrence of a conflict. In terms of the conflict monitoring account of Botvinick et al. (2001), the resource-depletion account suggests that not the detection of response conflicts is impaired under WM load but the execution of subsequent cognitive control enhancements after conflict trials. Note that these authors assume that control-triggered post-conflict adjustments lead to an enhanced representation of task demands which, in consequence, biases task-relevant stimulus processing. In the framework of that model, the need to update WM contents related to another task (like the arithmetic or the n-back stimuli) may impede the conflict-triggered updating of the Stroop task representation, resulting in a suppression of post-conflict adjustments.

However, we have to consider a second possibility how, in theory, increased WM demands may have affected the occurrence of post-conflict adjustments. According to that view, not the execution of cognitive control itself but already the detection of conflicts may be impaired by the concurrent WM task. It is important to note that this explanation does not imply that conflicts do not occur under WM load, but it assumes that participants do not become aware of these conflicts when they occur. As a consequence of such a view, we would have to assume that the conscious awareness of the conflict is a precondition for the operation of consequential control processes leading to trial-to-trial modulation of the RTs.

However, it is unclear whether the detection of a conflict by the conflict monitoring system requires the conscious awareness of conflict or whether it represents an unconscious, rather automatic process. Importantly, a recent study of van Gaal, Lamme, and Ridderinkhof (2010) showed that also unconscious conflicts lead to post-conflict adjustments. This finding is supported by an event-related potentials study which showed that conscious awareness of processing outcomes might not be a necessary pre-condition for the cognitive system to detect that something goes wrong or that a conflict is occurring (Pavone, Marzi, & Girelli, 2009). In particular, these authors found an error-related negativity in a visual discrimination task in error trials independently of whether participants became aware or non-aware of the error (see also Endrass, Reuter, & Kathmann, 2007). As the error-related negativity component is supposed to reflect the detection of errors as well as of response conflicts in the ACC (Masaki, Falkenstein, Stürmer, Pinkpank, & Sommer, 2007; Ullsperger & von Cramon, 2006; Yeung, Cohen, & Botvinick, 2004), this finding suggests that a possible unawareness of a conflict or error may not impair conflict detection itself. However, if that is the case, then the possible lack of awareness of a conflict which may have been caused by WM load would not be sufficient to explain the reduced post-conflict adjustments we observed, since conflict detection can occur even despite of unconsciousness of the error. Hence it is more parsimonious to explain the modulated post-conflict adjustments by a suppression of cognitive control enhancements.

A further alternative interpretation of our findings requiring discussion is that the WM demands in Experiment 1 and 2 may not have suppressed the exertion of cognitive control, but, in contrast, may have led to a tonically increased level of control such that no further transient post-conflict adjustments could occur. This claim may be based on the results of Plessow, Fischer, Kirschbaum, and Goschke (2011) who found that acute stress induces a high level of sustained control, while it depresses flexible control adjustments. If that account is correct, however, then a suppression of post-conflict adjustments should always be accompanied by a decreased Stroop effect even after congruent trials, since the increased level of control should result in a smaller congruency effect. In contrast to that prediction, the amount of the Stroop effect after congruent trials did not differ between the 0-back and the 1-back condition of Experiment 2, despite the suppressed post-conflict adjustments in the 1-back condition. Hence, the current data cannot be explained by the assumption that the WM tasks induced a high level of sustain control and, by this, impaired the exertion of post-conflict adjustments.

In addition, the present data also allow rejecting the possibility that the observed interference effects in conditions of high WM load can be explained by the need to switch between the WM and the Stroop task. Such task-switching processes were required by the 2-back, 1-back, and the 0-back conditions in Experiment 2. Importantly, the 0-back task required comparing the currently presented letter with the target letter in WM and deciding whether a response has to be executed in the current trial. Consequently, Stroop-0-back clearly represents an experimental condition in which participants permanently have to switch between the Stroop and the 0-back task. Since post-conflict adjustments in the Stroop-1-back and Stroop-2-back conditions were significantly reduced relative to the Stroop-0-back condition, a possible interference of task-switching processes with cognitive control alone cannot explain the observed effects. On the contrary, we believe that the specific processing characteristics related to the particular secondary task (i.e., WM updating) are the decisive characteristics, which affect the operation of post-conflict adjustments. The current findings are consistent with the assumption that tasks exposing sufficiently high WM demands affect post-conflict adjustments, while secondary tasks without such WM demands do not; this shows that pure switching between different tasks cannot be the reason for the disappearance of post-conflict adjustments in the current study.

Interestingly, not all studies investigating WM effects on cognitive control found an influence on trial-by-trial modulations. For example, Stürmer et al. (2005) reported that post-conflict adjustments in the Simon task were not suppressed when participants simultaneously performed a WM task (which was similar to the arithmetic task of Experiment 1). There are two possible reasons for the discrepancy between our findings and those of Stürmer et al.: First, although the WM task of Stürmer et al. was superficially similar to the arithmetic task in the present Experiment 1, it was less difficult than the present task. In particular, participants had to count up or down only in steps of one (instead of two), and, moreover, counting up was restricted to the arithmetic stimuli presented on one side of the screen while counting down to the stimuli of the other side. Therefore, this task was perhaps not sufficiently demanding to suppress the occurrence of post-conflict adjustments.

Another possible reason for the observed discrepancy in findings focuses on possible differences between the conflict processes in the two paradigms applied in the present study and the study of Stürmer et al. (2005). In detail, several theoretical accounts of response conflict assume that the processes in the Stroop and the Simon paradigm differ concerning their origins of conflict as well as their conflict resolution mechanisms. Thus, while conflicts are rather stimulus-based in the Stroop task, they are rather response-based in the Simon task (Kornblum, 1994; Kornblum, Hasbroucq, & Osman, 1990; Kornblum & Lee, 1995; Kornblum, Stevens, Whipple, & Requin, 1999; Zhang, Zhang, & Kornblum 1999). Concerning conflict resolution, there is evidence that cognitive control leads to an amplification of task-relevant stimulus-processing in the Stroop task while it leads to a suppression of the influence of task-irrelevant information on motor output in the Simon task (Egner et al., 2007; Egner & Hirsch, 2005a; Stürmer et al., 2002; Stürmer & Leuthold, 2003). Although conflict-related DLPFC activity was also found in the Simon task (Garavan, Ross, & Stein, 1999; Peterson et al., 2002), the effects of cognitive control on conflict resolution may differ between the Stroop and the Simon task (Egner, 2008). If post-conflict adjustments in the Stroop and the Simon task represent distinct forms of conflict regulation, then WM demands may have dissociable effects on these conflict-specific control processes.

One might have expected that WM processes should interfere also with within-trial control processes (Morishima, Okuda, & Sakai, 2010; Scherbaum, Fischer, Dshemuchadse, & Goschke, 2011; Taylor, Nobre, & Rushworth, 2007). As a consequence, this might have caused an increased Stroop effect in conditions of high compared to low WM demands. In contrast to that expectation, however, the amount of the Stroop effect did not differ between the low load and the high load conditions of Experiment 1 and 3, and it was even decreased in the 2-back compared to the 0-back and 1-back conditions of Experiment 2. If any, then this result pattern is not consistent with the assumption that WM load increases the current Stroop effect by harming current within-trial control processes; it may also suggest that within-trial control processes differ from the mechanisms involved in trial-by-trial post-conflict adjustments (Boy, Husain, & Sumner, 2010). The impact of WM load on the Stroop effect may also depend on the specific type of the applied WM task. For example, there is evidence that verbal and spatial WM load have dissociable effects on the congruency effect in the Simon task (Wühr & Biebl, 2011; Zhao, Chen, & West, 2010). However, since the focus of the present study was on the modulation of post-conflict adjustments, further research will be needed to clarify whether different WM tasks have also dissociable effects on within-trial control processes in the Stroop task.

It is important to note that the present data cannot be explained within the framework of a stimulus priming account (Davelaar & Stevens, 2009; Hommel et al., 2004; Mayr et al., 2003). Although we analyzed only trials which contained neither a repetition of the word nor of the color, significant post-conflict adjustments occurred in all experiments of the present study. Note that we could not simultaneously control for negative priming, since II trials contain either within-dimension repetitions (target or distractor feature is repeated as target or distractor feature, respectively) or across-dimension repetitions (target feature is repeated as distractor feature, or vice versa) in the version of the Stroop paradigm we used. However, further analyses revealed that the observed modulations of post-conflict adjustments remained stable when we excluded across-dimension instead of within-dimension repetition trials. Since the results of the present study consequently did not depend on which feature repetition trials were excluded, we conclude that it is very unlikely that our findings result from WM effects on feature priming. Note moreover that negative priming effects are typically very small relative to the size of the congruency effects (Fox, 1995; May, Kane, & Hasher, 1995) and are often not detectable when ISIs are longer than 2,000 ms (Neill & Valdes, 1992; Egner & Hirsch, 2005b).

In sum, the present study revealed that post-conflict adjustments in the Stroop task can be modulated by simultaneous WM updating demands. We predicted this modulation effect on the basis of evidence suggesting a common functional and neuroanatomical basis of WM and cognitive control processes. We speculate these two processes rely at least partially on the same capacity-limited processing resources, such that the resources necessary for post-conflict adjustments were depleted by the WM demands. An open question remains whether these findings can be generalized to conflict-related control processes in other paradigms. As Stürmer et al. (2005) did not find a suppression of post-conflict adjustments by WM demands in the Simon task, it is tempting to assume that WM processes interfere selectively with specific conflict resolution mechanisms.

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